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Review of Methods of Dose Estimation for Epidemiological Studies of the Radiological Impact of Nevada Test Site and Global Fallout

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Methods to assess radiation doses from nuclear weapons test fallout have been used to estimate doses to populations and individuals in a number of studies. However, only a few epidemiology studies have relied on fallout dose estimates. Though the methods for assessing doses from local and regional compared to global fallout are similar, there are significant differences in predicted doses and contributing radionuclides depending on the source of the fallout, e.g. whether the nuclear debris originated in Nevada at the U.S. nuclear test site or whether it originated at other locations worldwide. The sparse historical measurement data available are generally sufficient to estimate external exposure doses reasonably well. However, reconstruction of doses to body organs from ingestion and inhalation of radionuclides is significantly more complex and is almost always more uncertain than are external dose estimates. Internal dose estimates are generally based on estimates of the ground deposition per unit area of specific radionuclides and subsequent transport of radionuclides through the food chain. A number of technical challenges to correctly modeling deposition of fallout under wet and dry atmospheric conditions still remain, particularly at close-in locations where sizes of deposited particles vary significantly over modest changes in distance. This paper summarizes the various methods of dose estimation from weapons test fallout and the most important dose assessment and epidemiology studies that have relied on those methods.

INTRODUCTION

From 1945 to 1980, over 500 weapons tests were conducted in the atmosphere at a number of locations around the world (see Table 1). About 90 atmospheric tests were conducted at the Nevada test site (NTS). Fallout from atmospheric nuclear weapons tests carried out in Nevada from 1951–1958 resulted in generally low-level radiation exposure to the entire U.S. population. The highest NTS fallout doses were to populations living in the states immediately downwind from the test site. Fallout from the generally much larger tests carried out in the Pacific by the U.S. and in the former Soviet Union by the USSR from 1946 through 1962 resulted in low-level radiation exposure to the entire U.S. and world populations. In general, fallout from weapons testing resulted in relatively low doses to large numbers of people compared to the much higher maximum doses generally received from occupational exposure or by the survivors of the atomic bombings of Hiroshima and Nagasaki (*1*, *2*).

Land (*3*) and Gilbert *et al.* (*4*) have reviewed epidemiological studies of NTS fallout as well as related studies. Only two epidemiological studies of cancer risk to people downwind of the NTS involved detailed estimates of individual doses (*5–8*). These studies introduced some innovative and sophisticated approaches, but the doses in general were too low and too uncertain to provide improved new risk estimates, except for perhaps thyroid cancer (*3*). In addition to those epidemiological studies, a number of related dosimetry studies have also been carried out in recent years to estimate doses to populations and representative individuals (*9–11*). No epidemiological studies with detailed dosimetry related to global fallout have been reported, but numerous studies have been carried out to estimate collective doses to various populations. These include several recent assessments for both U.S. and world populations (*1*, *12*). Individual dose estimates have also been made for residents of the Marshall Islands who were exposed to local fallout from U.S. tests at Bikini and Eneweta k (*13*, *14*).

Although epidemiological studies of NTS and global fallout may not have provided useful information on cancer risk, due to the low doses, the methods developed for NTS and global fallout studies may prove useful for several current epidemiological studies where the doses are somewhat higher. For example, the dosimetry methods developed for studying NTS fallout were applied successfully to estimate doses from the fallout from the Chernobyl reactor accident

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TABLE 1
Number and Yield of Atmospheric Nuclear Tests with Off-site Fallout (*1, 2*)

	Global tests[a]	NTS tests
Number	457	86
Total yield (Mt equivalent TNT)	~439	~1

[a] Tests conducted outside continental U.S.

(*15, 16*) and may also be useful for estimating doses for a current National Cancer Institute (NCI) study (*17, 18*) of thyroid cancer in populations living downwind from the Semipalatinsk test site in the former Soviet Union (*19*). A number of general papers have been published on the topic of dose reconstruction for epidemiology (*20–22*). However, this paper specifically addresses the reconstruction of doses for retrospective studies of exposure to fallout. These generally involve special circumstances that differ considerably from studies involving occupational exposure. In particular, the absence of direct dosimetry data, either physical (i.e. personal dosimetry) or biological (bioassay data), requires the use of complicated models based on limited real data, which results in high uncertainty. The long interval since the exposures occurred has also resulted in loss of original data and questions regarding the quality of the data obtained. Limitations of memory recall related to lifestyle of many years ago increase the uncertainty in estimating doses to specific individuals.

This paper briefly summarizes the nuclear weapons testing programs and resultant fallout levels in the U.S., reviews the general principles and specific methods used to estimate doses to individuals and various populations, and summarizes the methods used in some of the recent epidemiological and related studies.

BACKGROUND AND METHODS

Exposure Pathways, Test Yields and Population Doses

Pathways of exposure from the fallout resulting from weapons testing include external irradiation, ingestion of radionuclides incorporated into food, and inhalation of descending and resuspended debris. The relative magnitude and geographic distribution of doses as well as the relative importance of external compared to internal exposure differed for NTS fallout and global fallout. Beck and Bennett (*2*) have reviewed the testing programs and related fallout deposition in detail. Bouville *et al.* (*12*) and DHHS (*11*) summarize the estimated doses within the U.S. from both NTS and global fallout.

Although the total yield of the tests carried out at the NTS was only about 1 Mt and the largest test only about 70 kt,[2] most of the tests were detonated close to the surface on towers or balloons and produced significant local and intermediate fallout (*2, 23*). The fallout was heaviest in areas immediately downwind from the NTS. Except for ^{131}I, the main impact was external exposure from short-lived radionuclides deposited on the ground, and most of the dose to individuals was delivered within a few months of fallout deposition. Doses from external exposure ranged from >3 mGy for residents of towns just downwind from the NTS to <0.25 mGy in the eastern U.S. (*9, 11, 23*). The average population dose from NTS fallout was about 0.5 mGy (*11*). Inhalation was not a major dose pathway, but ingestion of ^{131}I, primarily from consuming milk, resulted in significant thyroid doses to downwind populations. Thyroid doses to children ranged from 300 mGy in areas near the NTS to <1 mGy in some U.S. counties (*10, 11*). Average thyroid doses to all children born in 1951 were about 30 mGy (*10*).

In contrast, the total fission yield of atmospheric weapons tests carried out in the Pacific and Soviet Union (as well as at a few other sites by the UK, France and China) was about 200 Mt (*1, 2, 11*). However, due to the high yields of most of these tests (up to 50 Mt for a single test), much of the debris was injected into the stratosphere (*1*). Due to an average stratospheric residence half-life of about 1 year, most of the short-lived radionuclides decayed prior to re-entry into the troposphere and subsequent deposition. Thus, except for areas near the relatively sparsely populated test sites, most of the world's population was subjected primarily to exposure to long-lived radionuclides such as ^{3}H, ^{14}C, ^{90}Sr, ^{137}Cs and plutonium isotopes. External doses averaged to the U.S. population about 0.7 mGy (*11, 12*). With respect to global fallout, more deposition occurred in locations with greater annual precipitation. Hence higher external doses occurred in areas with higher average precipitation (*24*). Thus, in contrast to the situation for NTS fallout, the higher doses to the U.S. population from global fallout were in the wetter eastern states and the lower doses were in the more arid western states. Although the fission yield for global fallout was several hundred times that for NTS fallout, the average ingestion doses from ^{131}I from global fallout are estimated to have generally been lower than those from NTS tests (*11, 12*). However, contrary to the case for NTS fallout, ingestion doses were comparable to external exposure doses from global fallout due to the prevalence of long-lived nuclides such as ^{90}Sr and ^{137}Cs in soil. ^{14}C was also produced in large quantities in the high-yield thermonuclear tests; due to its extremely long half-life, ^{14}C will result in low-level internal exposure to the world's population for tens of thousands of years (*1, 11, 12*). Table 2 summarizes estimated average doses to the U.S. population from NTS and global fallout (*11*).

Principles of Estimating Doses to Individuals from Fallout for Use in Epidemiological Studies

This section discusses the specific methods that have been used to determine doses from external irradiation and from ingestion of contam-

[2] 1 kt and 1 Mt: explosive yield equivalent to 1000 and 1 million tons of TNT, respectively.

TABLE 2
Average Doses to U.S. Population (*11*)

	Global tests		NTS tests	
	Adult	Child born Jan. 1, 1951	Adult	Child born Jan. 1, 1951
Thyroid or red bone marrow external dose (mGy)	0.7	~0.7[a]	0.5	~0.5[a]
Thyroid internal dose (mGy)	0.7	2	5	30
Red bone marrow internal dose (mGy)	0.6	0.9	0.1	0.1

[a] Effective doses to young children are in actuality about 10–30% higher than for adults (*32*).

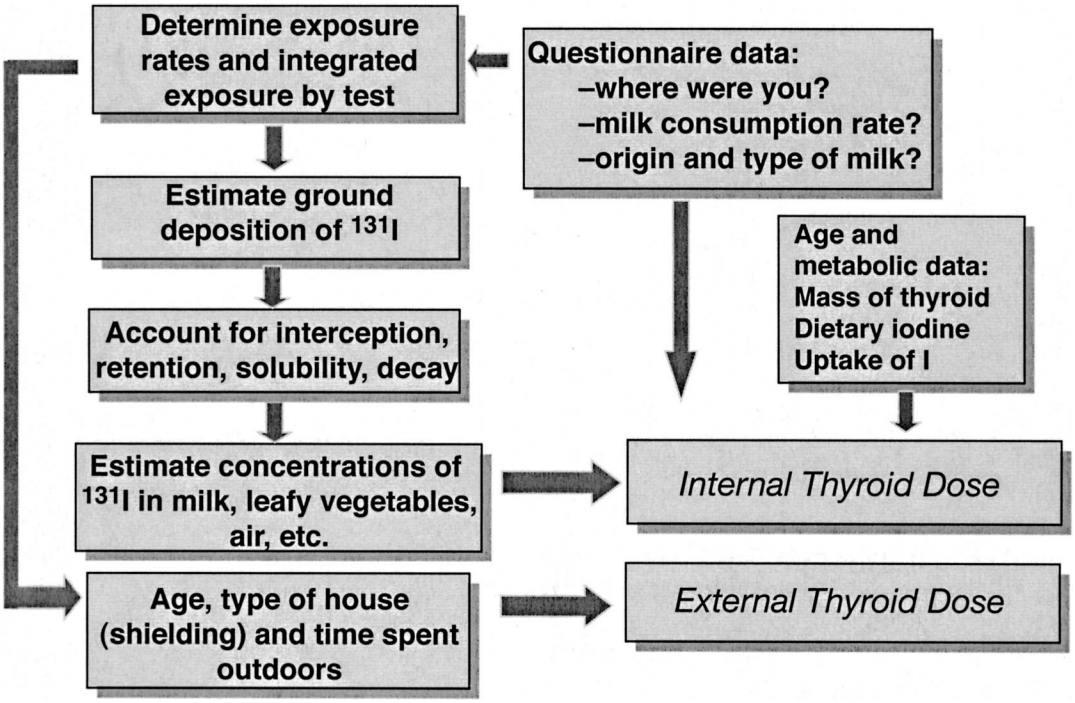

FIG. 1. Flow chart of typical steps and data required for reconstructing individual thyroid doses from fallout.

inated food. External radiation exposure and ingestion were the most important dose pathways. Other dose pathways such as inhalation of or immersion in contaminated air were much less important and are not discussed in this paper. For most individuals exposed to fallout, there were no direct measurements of dose. In contrast to occupational workers, the members of the public wore no dosimeters, exposure rates were monitored in only scattered locations, particularly at distances of more than a few hundred kilometers from the test site, and intakes were too low for bioassay measurements to be obtained using the technology available at that time. Thus, to reconstruct doses to individuals, one must employ models that relate measured quantities such as exposure rates or measured nuclide activity in soil or air to dose. Furthermore, due to the scarcity of actual data, deposition densities and/or exposure rates at any particular location may have to be inferred by interpolation of available data. Estimates of exposure rates often have to be inferred from available deposition data or vice versa. Finally, doses to individuals depend on reconstructions of their individual lifestyles during the fallout and in the immediate months afterward, i.e., where they resided during each test, when as well as how much time they spent outdoors, the effectiveness of the building shielding when indoors, dietary intake, and sources of food (particularly milk and vegetables). Figure 1 shows the primary steps for the estimation of thyroid dose from fallout and the data required as discussed above.

External doses. The starting point for calculating external exposure has usually been the estimation or measurement of the instantaneous exposure rate at locations frequented by the individual. Conversely, a measurement of the deposition density[3] of any particular nuclide has been used to reconstruct the temporal dependence of exposure rate for NTS fallout using information available on the relative concentrations of each nuclide in the fallout per unit exposure rate for each NTS test (*25*) and conversion factors relating deposition density to exposure rate (*26*). Deposition of total β-particle activity measured on gummed film or in soil has been used to estimate deposition of specific nuclides (*27*), again using the information on the nuclide composition of fallout for specific tests. Because the geographic distribution of measurement data is sparse, particularly in areas remote from the test site, available data must be interpolated to provide estimates at a useful spatial resolution. For NTS fallout, survey-meter measurements obtained in areas close to the NTS were interpolated to estimate exposure rates in many towns and to develop detailed deposition patterns in areas immediately downwind from the NTS (*28*). For areas more remote from the NTS, deposition densities and resultant exposure rates were estimated from interpolating gummed-film data (*28–30*) or from inferring NTS ^{137}Cs deposition from retrospective soil sample analyses of long-lived ^{137}Cs and plutonium isotopes (*31*). In the latter method, the current total inventory of ^{137}Cs in soil samples was partitioned into ^{137}Cs from NTS fallout and ^{137}Cs from global fallout using the measured isotopic ratio of ^{240}Pu/^{239}Pu in the sample. The ratio of these plutonium isotopes is much higher for global fallout than for NTS fallout due to the much higher neutron flux created by the high-yield thermonuclear tests, and the ratio of ^{137}Cs to plutonium in global fallout is well established. The estimated ^{137}Cs from NTS fallout, when decayed back to the years of testing, along with the information on the relative nuclide composition of NTS test fallout and estimated time of fallout arrival, allows a determination of the deposition density of other radionuclides, and the resultant exposure rate, from NTS fallout.

For global fallout, where the initial nuclide composition of debris for individual tests is not available (existing data are classified), the external exposure rates and/or specific nuclide deposition usually must be estimated from actual measurement data supplemented by models to interpolate such data as a function of time and location. Precipitation records can be used to estimate the geographic variation (*2, 24*). Considerable data, particularly for ^{90}Sr in precipitation and in soil and exposure rates at various locations exist from extensive monitoring (*1, 2*). Data on the ratios of various nuclides in fallout have been estimated from measurements in air samples and precipitation at scattered sites and from model calculations (*2, 24*).

Once the time dependence of exposure rates has been estimated for specific locations, the exposure to particular individuals can be estimated by assuming the time spent outdoors and indoors at various locales, the reduction in exposure rate with increasing time due to decay and weath-

[3] Deposition density refers to the total amount of activity of a specific radionuclide deposited per unit area; an example of units would be Bq m^{-2} of ^{137}Cs.

ering (resulting from penetration of nuclides deeper into the soil or wash-off from building and other surfaces) and applying a shielding factor based on the type of structure to the estimated fraction of time spent indoors. The dose to a particular organ or the average whole-body dose can be estimated from the exposure. The dose per unit exposure in air differs slightly, depending on age (body size) and orientation with respect to the radiation source (*32*). The doses to children are generally about 10 to 30% higher than that to an adult (*32*).

Ingestion doses. For NTS fallout, measurements of the time dependence of exposure have been used to estimate the deposition density of most nuclides using the information on nuclide composition available for each test. Given the deposition of a particular nuclide, the ingestion dose has been estimated from models relating concentration in soil and on vegetation to levels in food ingested by animals and humans (*6, 9, 10, 33, 34*). This often required a fairly complex analysis to determine whether animals such as cows were on fresh pasture during deposition of short-lived nuclides such as ^{131}I (*6, 10, 34*) and how the deposition in one location has an impact on the food consumed at another (*10, 33, 35, 36*).

Estimating the doses to a specific individual requires a description of the lifestyle and diet of the individual. This includes his/her location at various times after deposition. The intake of various nuclides can then be estimated and combined with a calculated dose coefficient that relates intake to dose (i.e. Sv Bq^{-1}) to estimate the dose to a particular organ (*32*).

Although body burden measurement data for the years of atmospheric nuclear testing are sparse, they can be used to validate models when and where available. Considerable data on body burdens and nuclide concentrations in various foods are available for global fallout (*2*). If data on levels in food have been obtained at various locations, they can be used to validate models or to provide better estimates for specific individuals.

Models to describe quantitatively the transport and movement of radionuclides in the environment are used to estimate radionuclide concentrations in plants, meat, milk, etc., but the uncertainty is high. Because most atmospheric nuclear testing took place over 40 years ago, lifestyle information for specific subjects in any epidemiological study will be very uncertain due to difficulties of recall.

Uncertainty of dose estimation. Because estimates of dose to individuals from fallout are highly uncertain, a dose reconstruction, particularly one in support of an epidemiological study, must provide credible estimates of uncertainty (*37*). Many factors, however, contribute to the overall uncertainty.

As mentioned, little monitoring was done for NTS fallout except at close-in sites; hence the deposition-density estimates for most U.S. locations are very uncertain. The deposition-density data that have been used to calculate internal and external doses from NTS fallout for most of the U.S. population, for example, were based on interpolation of data from less than 100 monitoring sites (*10, 11, 30*). For global fallout, there were even fewer monitoring sites in continuous operation, and the estimates of deposition density for short-lived nuclides such as ^{131}I are even more uncertain (*11, 12, 24*).

For epidemiological studies, one generally needs to estimate the dose to specific organs of specific individuals or population groups from all significant exposure pathways. Because there can be significant biological variability among individuals, even if one were able to estimate the intakes of radionuclides ingested fairly accurately, the uncertainty in the resultant dose to that individual would still likely be great. This factor, combined with the large uncertainty in estimating intakes and deposition density at any location from sparse data on fallout that occurred many years previously, results in the uncertainty in doses to specific individuals being much higher than estimates to population groups or nonspecific individuals. Estimates of the uncertainty have often been expressed as a geometric standard deviation (GSD) because the probability density functions describing either the range of dose for a representative person or the true dose for a specific individual are approximately lognormal. GSDs for doses calculated for nonspecific individuals from ingestion of ^{131}I from NTS fallout typically ranged between 2.5 and 3.0 (*10*); GSDs for identified persons in a cohort study were similar; 95% were below 3.5, though there were a few isolated cases of GSDs between 5 and 7 (*6*).

Some of the specific methods developed to reconstruct doses for NTS and/or global fallout discussed above have been applied in the epidemiological and related studies discussed in the next section.

DOSIMETRIC AND EPIDEMIOLOGICAL STUDIES OF NTS AND GLOBAL FALLOUT

This section summarizes the dosimetry methodologies used in several dose assessment and epidemiological studies as well as selected findings from those studies. Table 3 summarizes the information provided here; more detailed information can be found in the cited references.

ORERP Study

The first major comprehensive dose reconstruction for NTS fallout was the Offsite Radiation Exposure Review Program (ORERP), a multi-institution effort that attempted to reconstruct radiation doses along with credible estimates of uncertainty (*9*). Doses were calculated for specific individuals involved in a class action lawsuit against the U.S. government, as well as for unspecified representative persons in a number of western states (Nevada, Utah, Arizona, New Mexico and parts of Colorado, Idaho, California, Wyoming and Oregon) from all exposure pathways. During the course of that study, 1979–1985, a number of key issues for fallout reconstruction were addressed, and many important methods and databases were developed. A federal advisory committee, the Dose Assessment Advisory Group (DAAG), provided oversight to the project. The DAAG consisted of eminent scientists as well as citizen representatives appointed by the governors of Utah, Arizona, Nevada and California (*9*).

One of the more important accomplishments of the ORERP was to review and gather together all the relevant historical data in a central location, the Coordination and Information Center (http://www.nv.doe.gov/about/cic.htm). Databases of survey-meter data (*28, 38*), median doses and arrival times of fallout in downwind towns (*39*), and median doses for more distant counties as far west as Colorado were developed (*40*).

Another key development was the determination of the mixture of radionuclides in fallout from each test (*25, 41*). Those results, discussed earlier, were based on data on the concentrations of various nuclides measured in the debris cloud immediately after the test and now-known fission yields. Subsequently, complex calculations were carried out to determine the activity of each radionuclide as a function of time after each NTS test. Those calculations of deposition density accounted for fractionation and were normalized to unit exposure rate using conversion factors developed by Beck (*26*) specifically for the ORERP project and allowed one to relate measurements of exposure rates at various times to concentrations of specific nuclides in fallout from that test.

TABLE 3
Summary of Dosimetry and Epidemiological Studies of Fallout-Related Exposures

Study	Source of fallout	Purpose of study	Dosimetric outcome	Summary of dose estimates (mGy unless otherwise noted)	Primary reference(s)
Off-site radiation exposure review project (ORERP)	Nevada Test Site (NTS)	Develop methods and databases for reconstructing doses from NTS fallout with application to damage claims against U.S. government	External and internal dose estimates for representative persons in NV, UT, AZ, NM, CO, ID, CA, WY and OR	Phase I area collective external dose was estimated to be 470 man-Sv	*9, 39, 40*
Utah leukemia case-control study	NTS	Conduct analyses to detect excess risk of leukemia as a function of external γ-ray dose from NTS fallout	Bone marrow dose estimates for 1,177 leukemia cases and 5,330 controls in Utah	0 to 29, mean = 2.9, median = 3.2	*5, 7*
Utah thyroid cohort study	NTS	Conduct analyses to detect excess risk of thyroid neoplasia as a function of radiation dose from NTS fallout	Thyroid dose estimates (external + internal radiation) for 3,545 persons in cohort in UT, NV and AZ	Washington, CO, UT = 170 (median), 720 (mean) Lincoln, CO, NV = 28 (median), 50 (mean) Graham CO, AZ = 3.6 (median), 13 (mean)	*6, 8*
National Cancer Institute (1997)	NTS	Respond to P.L.97-414 to develop credible estimates of thyroid dose from ^{131}I released from nuclear test at the NTS	Thyroid dose estimates from ^{131}I for representative persons in all counties of U.S. Doses varied by county or residence, age at exposure, and milk consumption rate	Examples: Salt Lake City: 100 (born 10/1/1951), 55 (born 11/28/1956) New York City: 50 (born 10/1/1951), 22 (born 11/28/1956)	*10*
DHHS (2003)	NTS and Global Tests	Respond to Congressional mandate to investigate the feasibility of estimating doses to the entire U.S. population from all radionuclides in NTS and global fallout	Dose estimates (external, thyroid, red bone marrow) to representtative persons in U.S. from all major fallout radionuclides. Doses from radionuclides other than ^{131}I estimated on a county basis.	See Table 2 of this publication	*11*
Marshall Islands	Bikini and Enewetak, Marshall Islands	1. Evaluate thyroid nodule prevalence as a function of distance from Bikini as an indicator of dose	1. Used distance as a surrogate of thyroid radiation dose at inhabited atolls	1. No doses estimated	1. *51*
		2. Re-evaluate findings published in ref. (*50*); investigate prevalence of thyroid cancer and conduct analyses for excess risk of cancer and benign thyroid conditions as a function of dose	2. Developed two dose-related estimators as surrogates for true dose and age-specific estimates at all inhabited atolls (normalized to 1-year-old child at Utrik atoll)	2. Examples: 0.24 to 1.0 (median 0.39) at Utrik Atoll, 0.17 to 0.66 (median 0.29) at Likiep Atoll, 0.006 to 0.024 (median 0.008) at Majuro Atoll (doses normalized to 1-year-old at Utrik)	2. *52–54*
Kazakhstan	Semipalatinsk, Kazakhstan	Conduct analyses to detect excess risk of thyroid neoplasia as a function of radiation dose from local fallout and estimate RBE for internal ^{131}I radiation	Dose estimates for ~3,000 persons living in eight study villages	Total (external + internal) thyroid dose varied by village: ~40 in control villages to 4400 in most highly exposed village	*17, 18*

A third major development was the application of a method used by Beck and Krey (*31*) in an earlier study of NTS fallout in Utah, to extend estimates of fallout deposition to areas beyond the close-in areas where extensive survey meter measurements had been made. This method, described previously, allowed estimates of NTS ^{137}Cs deposition density. Coupled with the tables developed by Hicks, retrospective estimates of deposition density of all

other nuclides could be made from contemporary soil analyses. Consequently, hundreds of soil samples were collected at sites in the study region (*28, 40*). Those data, supplemented by various other data and meteorological model calculations of fallout patterns, were used to construct the County Database described above.

To estimate ingestion doses, the ORERP supported the development of a dynamic model relating deposition density to concentrations in vegetation and subsequent transfer to animals and foodstuffs. This pathway model was unique in that it also was the first model of its type to include the capability to conduct comprehensive stochastic uncertainty analyses (*42*).

The databases and innovative methods developed for the ORERP study were used in the epidemiological and other subsequent studies described below. The dosimetry results are excerpted here from the 2000 UNSCEAR report (*1*). The external effective dose exceeded 3 mSv in 20% of the 180,000 people residing in the ORERP Phase I study area (including Clark, Lincoln and Nye Counties, NV and Washington County, UT). The highest external effective doses were in the range 60–90 mSv, and the population-weighted average value was 2.8 mSv. The exposures resulted primarily from short-lived γ-ray emitters (half-lives $<$100 days). Most of the exposures resulted from relatively few events; 90% of the cumulative collective external dose of 470 man-Sv resulted from 17 events, the most significant being test Harry on May 19, 1953 (180 man-Sv), test Bee on March 22, 1955 (70 man-Sv), and test Smoky on August 31, 1957 (50 man-Sv). Collective external doses that included areas further downwind, encompassing all of Nevada and Utah and parts of several other western states, were estimated to have been even greater than those for the local area, about 10,000 man-Sv, primarily due to the exposure of the large population in areas around Salt Lake City. Internal exposures resulting from atmospheric testing at the Nevada test site were estimated from deposition measurements and an environmental transfer model. Absorbed doses to organs and tissues from internal exposure were substantially less than those from external exposure, with the exception of the thyroid, in which ^{131}I from ingestion of milk contributed relatively higher doses.

Utah Leukemia Case–Control Study

The Utah leukemia case–control study sponsored by the National Cancer Institute (NCI) and carried out by the University of Utah and collaborating scientists studied the relationship between deaths due to leukemia among residents of Utah during the years of NTS fallout and external exposure from that fallout (*5, 7*). University of Utah scientists estimated fallout deposition and external bone marrow doses for 1,177 cases and 5,330 controls using the Town and County databases developed in the ORERP project supplemented by an ''Other Locations'' database that was developed by University of Utah investigators. The ''Other Locations'' database relied heavily on estimates of deposition density made from β-particle activity collected on gummed-film at sites in surrounding areas (*29*). Residence histories of cases and controls (all deceased at the time of the study) were determined from records of the Church of Jesus Christ of Latter Day Saints (LDS), from local and regional phone directories, and from other sources. Those data were then used to estimate total doses from external exposure doses using the general methodology described earlier in this paper. The dosimetry included an assessment of uncertainty that accounted for imprecision of estimates of fallout time of arrival, residence history, and other factors. The median dose for all cases and controls was 3.2 mGy. The maximum bone marrow dose to any subject was estimated to be 28 mGy.

Utah Thyroid Cohort Study

This Utah thyroid cohort study was also sponsored by the NCI and carried out by University of Utah investigators and collaborating scientists (*8*). Similarly to the leukemia study, there was heavy reliance on the deposition-density estimation methods developed by the ORERP to estimate deposition of ^{131}I in Utah. Deposition on plants (*43*) and subsequently in milk supplies and other foods was estimated. Estimates of thyroid dose to members of the cohort and an out-of-state group were calculated, again based on extensive surveys of lifestyles (amount of milk consumed, locations during fallout, etc.) with use of an approved questionnaire. This study involved a detailed determination of pasture practices and milk distribution in Utah to relate deposition density to ^{131}I intake by humans (*6, 36*). Thyroid doses for the 2,473 subjects in the cohort ranged from 0 to several grays. The study was probably the first large epidemiological study related to fallout exposure to propagate uncertainty on an individual subject basis. Currently, dose estimates are being re-evaluated and updated with some more current information.

NCI Study of Doses to the U.S. Population from ^{131}I

A Congressional mandate required the NCI to estimate the doses received by the entire U.S. population from the ingestion of ^{131}I deposited in fallout from NTS tests (*10*). Previous studies provided detailed deposition data only for states as far to the east of the NTS as Colorado and New Mexico. The NCI study attempted to estimate the average deposition density of ^{131}I in each county of the contiguous U.S., primarily by interpolating daily deposition data from 100 or fewer continuously operating monitoring sites. Those monitoring sites collected fallout daily on gummed film (sticky paper) and were sent to the Health and Safety Laboratory (HASL) in New York City where the deposited β-particle activity was measured. Using methods reported previously by Beck (*27, 29*) and refined for the NCI study (*10, 30*) along with sophisticated interpolation based on kriging and precipitation data, the measured β-particle ac-

tivities were used to infer the deposition of ^{131}I on the ground at locations nationwide. Median daily deposition estimates of ^{131}I were made, along with uncertainty estimates, for all counties not included in the original ORERP study.

Models of interception of fallout on vegetation, milk pasture practices in various areas of the country, milk distribution patterns, and milk consumption trends were used to estimate average intakes of ^{131}I from consumption of fresh cows' milk, as well as from other sources, and from those data the median thyroid dose to various age groups exposed to NTS fallout was calculated. Because of the high public interest in this project and its conclusions, the NCI asked the National Academy of Sciences/National Research Council to review the methodology and results (*44*). In its review, the Academy committee noted that based on its study, the NCI subsequently estimated that exposure to ^{131}I from Nevada weapons tests will produce between 11,300 and 212,000 excess lifetime cases of thyroid cancer with a central estimate of 49,000 cases (*44*).

This was one of the first studies of NTS fallout to provide a geographic distribution of fallout by county, particularly for ^{131}I, across the U.S. One important finding of the study was that it illustrated that the higher doses were not always to persons living in areas of greatest fallout. At least for ingestion, the higher doses were to individuals who obtained their milk from the areas of higher fallout during times when cows were on fresh pasture.

DHHS Feasibility Study

One of the questions raised in the NAS review of the NCI nationwide ^{131}I study (*44*) was the significance of the dose to the U.S. population from external exposure, from nuclides other than ^{131}I, and from global fallout. In 1999, Congress requested HHS to investigate the feasibility of estimating doses to the entire U.S. population from NTS fallout, as well as from the later-deposited global fallout, with a geographic resolution similar to that as the NCI ^{131}I study. A draft study (*11*) conducted by the NCI, CDC and consultants was issued in May of 2002 and reviewed by the National Academy of Sciences/National Research Council in 2003 (*45*). The draft study illustrates that it is feasible to provide reasonable estimates of average external and ingestion doses on a county-level basis, for all important radionuclides, for both NTS and global fallout. The uncertainty in such estimates is lower for radionuclides with half-lives of several months or longer than for shorter-lived nuclides. The amount of measurement data for shorter-lived nuclides is very limited. In addition, the transport and deposition of a short-lived nuclide such as ^{131}I, which is of particular interest to scientists as well as the public, is difficult to model when it originates from global fallout because the models are very sensitive to the fraction of the debris injected into the stratosphere as opposed to the troposphere, which varies from test to the test, and the residence time of the debris in the stratosphere (*2, 24*).

Bouville *et al.* (*12*) and Beck and Bennett (*2*) summarize some of the preliminary results from this feasibility study. As discussed earlier, the geographic pattern of fallout differs for NTS and global fallout, and thus persons residing in the eastern states received higher external and internal doses from global fallout than from NTS fallout, while the opposite was generally true for residents of western states. The dose to any particular individual, however, depends on where and when he/she was exposed and his/her particular lifestyle during the periods of fallout.

Marshall Islands Studies

In addition to studies of human exposure to NTS and global fallout, there have been several reports on present-day and prospective doses to residents of the Marshall Islands as a consequence of fallout and residual radioactivity in the environment from nuclear testing carried out by the U.S. at Bikini and Enewetak atolls. Reconstructions of doses received by the Marshallese from early fallout are few in number, and estimates are primarily found in agency and laboratory reports (see for example ref. *46*). Most all the estimates of thyroid doses to residents of inhabited islands that were heavily contaminated by local fallout from BRAVO in 1952 relied on data on ^{131}I measured in pooled urine samples collected shortly after the event (*13, 46*). However, doses have been estimated for specific population groups, and exposed islanders have been monitored medically over many decades (*13, 47–49*).

Studies of health effects from fallout from the Marshall Islands have been limited primarily to examinations of Japanese sailors exposed on the fishing vessel Lucky Dragon (*47*) in the waters off Bikini atoll, to long-term health and cancer surveillance (*48–50*) of the populations directly exposed to early fallout (residents of Rongelap and Utrik atolls), and to two contemporary epidemiological studies, one of benign thyroid disease (*51*) and one of thyroid cancer and benign diseases (*52–54*).

Estimating doses received by the Marshallese from fallout during the 1950s is difficult because of the scarcity of data required for dose reconstruction. For example, there was only one gummed-film station in the Marshall Islands at the time. Moreover, the significance of the exposure pathways for the Marshallese differs appreciably from those of the exposure scenarios in the U.S. Primary lifestyle differences relate to diet, an example being the absence of the cow-milk pathway and a high reliance on native fruits, e.g. coconuts. In assessments for the Marshallese, there is also increased importance of direct deposition of fallout onto foods and utensils, possibly a greater importance of inhalation doses, and less protection from external radiation because of thinly constructed houses.

The first of the two epidemiological studies mentioned (*51*) used distance from Bikini atoll as a surrogate to thy-

roid radiation dose. That study, conducted in the early 1980s, reported a decreasing prevalence of benign thyroid nodules with increasing distance from the Bikini test site. Prevalence was determined by physical examination (palpation). The second epidemiological study (*52–54*) examined approximately 65% of the population alive at the time of the largest test in the Marshall Islands (BRAVO, March 1, 1954) during the years 1993 through 1997. Prevalence was determined through the use of physical examinations (palpation), ultrasound and fine-needle biopsy to determine if suspicious nodules were cancerous. Two surrogates for internal dose were determined, the exposure rate at the time of fallout deposition and the integral external exposure. The study assumed that both surrogates were correlated with internal thyroid dose and estimates were made using contemporary measurements of ^{137}Cs and the nuclide composition for BRAVO fallout developed by Hicks (*55*). That epidemiological study, though still ongoing, to date has not found a relationship between nodular disease and distance or either surrogate of internal dose, and has found a minimally significant relationship between dose and prevalence of thyroid cancer.

For the purposes of present-day and prospective assessments, the islands have been monitored extensively for current deposition density of long-lived nuclides such as ^{137}Cs, ^{90}Sr and plutonium (*14*). Activity levels in soil, fish, biota, etc. have also been monitored extensively and used in those projections.

DISCUSSION

A number of problem areas are in need of further study to improve estimates of doses from nuclear weapons testing fallout. Some of these have been brought to the fore by a current NCI-sponsored study of thyroid doses to populations who lived downwind from the Semipalatinsk test site in Kazakhstan (*17, 18*). The earliest assessments for Kazakhstan did not consider that accounting for fractionation was important since most of the refractory elements were associated with large particles and fell out of the debris cloud at close-in locations Thus, as discussed by Hicks (*41*), the mixture of radionuclides was assumed to have generally stabilized at distances of interest to U.S. studies such as ORERP. However, much of the population of interest in Kazakhstan lived at close distances where fractionation may have significantly modified the radionuclide mixture. The particle size distribution and extent of fractionation are very important in estimating the fractions of the important biologically significant radionuclides, such as ^{131}I, that are intercepted by vegetation (*56, 57*). Dose reconstruction methodology used in the former Soviet Union differs somewhat from U.S. methods in that much more attention has been given to this problem as well as to describing the variation in the solubility of nuclides deposited on vegetation as a function of distance from the detonation site (*58*). The NCI is currently working closely with scientists from the Institute of Biophysics in Moscow to reconcile differences between these dose reconstruction methods and those used in U.S. studies particularly for areas close to test sites. The cooperation is likely to improve our understanding of fractionation, interception by vegetation, and solubility of fallout. It is expected that this group effort will allow better estimates of doses to be made to support the Kazakhstan epidemiological study.

Further studies of global fallout doses are not likely to be useful for epidemiological purposes because of a variety of factors, primarily the requirement for unreasonably large cohort sizes and the multiple confounding factors; however, public interest may mandate some additional effort. Areas of study where improvements could be made are in the identification of localized regions of unusually high deposition (so-called ''hot spots'') and the identification of subgroups of the most highly exposed individuals, particularly with respect to exposure to ^{131}I. Declassification of data on fission product composition for specific U.S. Pacific tests as well as fission/fusion ratios for individual tests could assist in producing better estimates of doses from short-lived nuclides (*11*).

Finally, it is worthwhile to note that fallout from nuclear weapons tests has resulted in a worldwide addition to background radiation, primarily from the long-lived radionuclides such as ^{137}Cs and plutonium isotopes. This background must be considered in current assessments involving cleanup of contaminated weapons production sites. Fallout-related dose also may need to be accounted for in certain epidemiological studies involving sources other than fallout. For example, doses to the thyroid from ^{131}I from weapons test fallout were considered in an epidemiological study of thyroid disease conducted at Hanford, where regional populations were exposed to local releases of ^{131}I (*59*).

CONCLUDING REMARKS

A number of generalizations and specific points can be drawn from this review of dosimetric methods for weapons test fallout.

1. Reconstruction of doses from fallout from weapons tests generally relies on estimates of deposition density and on sophisticated pathway models relating deposition density to potential dose.
2. The quantity and quality of the data used to estimate deposition density, as well as other important data, vary by location and time, making a comprehensive uncertainty analysis essential.
3. The doses received as a result of exposure to fallout have generally been small compared to lifetime exposure from background radiation, but dose estimates are very uncertain as well (particularly for specific individuals). Because large numbers of persons have been exposed to weapons test fallout, it is unique in terms of manmade sources of environmental radiation.

4. In general, population average doses are more accurate than individual doses but less useful for epidemiological studies. It does appear feasible, however, to reasonably estimate doses that can be used in epidemiological studies.
5. A few epidemiological studies using dose reconstruction have been carried out on populations exposed to NTS fallout, but they have provided little new information on risk, primarily because of limitations on cohort size, confounding factors, or, in some cases, because doses were too low to cause an effect large enough to be detected.
6. If future dose or health-related studies are planned, there is a need to preserve historical data. Although much of the data on NTS fallout has been collected in a central location, data on global fallout are scattered widely and original data are often no longer available. A dedicated search and archival program begun immediately would almost certainly be beneficial to future programs of study.
7. The methods developed to study NTS and global fallout dose reconstruction have proven useful for other exposure situations, e.g. other nuclear test sites (Marshall Islands, Kazakhstan, etc.) and releases from weapons production facilities (e.g. Hanford), as well as from accidents involving reactors (e.g. Chernobyl). The dose reconstruction methods for fallout continue to be useful, for example, in a present study of thyroid disease amongst populations living downwind from the former Soviet Union's (FSU) Semipalatinsk test site.
8. Some additional research is still required, particularly with respect to deposition of close-in fallout.

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